# Optimal Conjunctive use of Groundwater and Surface Water in an Irrigation Network

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## Abstract
This paper develops a non-linear optimisation model for the determination of the optimised water allocation and cropping pattern under adequate and limited water supplies. The water productivity defined as the net benefit to the volume of allocated water was considered as the objective function. Decision variables are the cultivated area and water allocated to each crop. A standard piece of common software named Ms Excel Solver has been used in order to solving the objective function. The proposed model was applied to Ghazvin Irrigation Network located in a semi-arid region in Iran. The results showed that among the crop types grown in the region, onion and alfalfa have the highest and the lowest water productivity values, respectively. The values under wet years as optimal cropping pattern were estimated at 75.068 and 3.054 Rls/ML (1 Rls = 0.0012 $US) for onion and alfalfa, respectively. The findings indicated that the overall water productivity of the irrigation network with relevant cropping pattern management may be increased to as high as 12.665 Rls/ML under dry years. This is while in the normal and wet years, depending on the water available and the cropping pattern, the values were estimated to be 15.592 and 12.881 Rls/ ML, respectively. Hence, the results demonstrated that the water productivity of irrigation network can be improved as result of optimal cropping pattern. For the study area, the maximum variations of the water productivity may be fixed around 18 % for different water regimes. The evaluations illustrated that the proposed model can be used as an effective tool to determine optimal irrigated cropping patterns under water scarcity constraints. The model determines the optimal distribution of areas and crops, the water allocation, and the profit. Moreover, the model can be used to explore the possibilities of conjunctive use options of surface and groundwater in the study area, which would enhance the overall benefits from cropping activities.

*Keywords: Cropping pattern, irrigation scheduling,; water productivity, irrigation network, non-linear model*

## 1 Introduction

In most countries, planning and management of water resources has become a very important issue. Part of this problem, accurate estimation of water demand by agriculture is a key need for water management. Cropping pattern is one of the most important parameters involved in irrigation network design. It is directly related to productivity of irrigation systems and greatly contributes to improved land and water utilization. In its initial design stages, the cropping pattern for each locality is developed on the basis of local and temporal considerations with due attention to major policies of the agriculture sector and then used as the basis for designing the physical structure of the irrigation works. Once in operation, the cropping pattern may undergo great changes in terms of crop type and crop density. The major causes for these changes may be included: (1) changes in economic value of crops; (2) variations in quantity of supplied water over different water period; (3) changes in farm management practices; (4) rapid technological advances resulting in agricultural mechanization; (5) changes in major national/regional policies in the agriculture sector; and (6) inadequacies and failures of irrigation network operational management.

Appropriate and timely planning and decision-making for revisions and changes in cropping patterns over short periods (especially over dry periods) will enhance the system productivity and will additionally make it possible to exercise a demand-based water management with due consideration for impacts on water resources. Furthermore, optimal cropping pattern interacts with water consumption and crop yield, as well as with optimal profitability, and can, therefore, play an important role in improving irrigation network management through its impacts on increased income levels and water use efficiency.

Economic evaluation of irrigation management often requires the quantification of crop response to irrigation. Study of plant response to irrigation management practices has been going on for more than a century now and a great many recommendations and different relations have been proposed, along these lines, to investigate and determine irrigation water demand and plant response to different combinations of planting dates, quantities of resources, and decision-making criteria. Over the past two decades, different methodologies as well as simulation and optimisation models have been developed for designing, planning, and operating water resources. A number of these models focus on water distribution optimisation while others concentrate on economic optimisation, and still others aim at both objectives simultaneously. An inadequacy in most of these models is their failure to capture the logical and practical relationship between the water quantity that can be supplied and the demand for water (Diaz and Brown, 1996). The simplest optimisation model is one that allows for calculation of optimal water application depth for a single crop with the objective of maximizing the profit function regardless of any water limitation (Young, 1996). Some researchers have used analytical optimisation methods in which changes in optimization conditions are possible for cases where limitations in land and water resources have to be considered (Yaron and Bresler, 1983; English, 1992). According to economic optimisation models, cropping pattern is considered for water and land allocations among different crops at the farm or at the irrigation area levels.

Carvallo et al. (1998) developed a non-linear optimisation problem for the determination of optimal cropping patterns. They used GAMS-MINOS software package to solve the problem. Kuo et al. (2000) proposed a genetic algorithm optimisation model for the optimal cropping patterm in an irrigation scheme. Sabu and Sudhindra (2000) proposed a model based on both stochastic dynamic programming and deterministic dynamic programming for the optimal cropping pattern in a canal command area. Reca et al. (2001b) proposed an optimisation model for the distribution of water in an irrigation network under dry conditions. The objective was to determine the maximum water use of single crops. Leenhart et al. (2004) proposed the ADEAUMIS model to estimate the water demand for water resources management on a regional scale and used it for a region in southern France. Benli and Kodal (2003) developed a non-linear optimisation model for water distribution at the farm level with limited water resources in the southeast of the agricultural site in Anatolia, Turkey. They compared the results obtained from the model with those from a linear model to show that the non-linear optimisation yielded better results than the linear one did. Mainuddin et al. (1997), Amir and Fisher (1999), Singh et al. (2001), Kipkorir et al (2002), Ghahraman and Sepaskhah (2004), and Li et al. (2005) used both linear and non-linear optimisation techniques in their studies of optimal cropping pattern to maximize net profit from farms.

The purpose of the present paper is to develop and apply a simple optimisation model to determine the optimal cropping pattern at different water availability levels for a real irrigation network. The water productivity defined as net profit to the volume of allocated water is taken to be the objective function of the model. A standard piece of common software named Ms Excel Solver has been used in order to solving the objective functions.

## 2 Material and methods

### 2.1 Mathematical model

It is assumed that in the case of insufficiency of total water supply, the limited water should optimally be allocated to different units and crops. When a given amount of water is allocated to a crop it is necessary to optimally distribute the amount of water through different growing seasons. In developing the model, crop response to actual evapotranspiration function was used as proposed by Stewart and Hagan (1973). This is one of the most practical relations used in the field and confirmed by FAO, which is also used by other researchers including, De Juan et al. (1996), and Reca et al. (2001a). The relation is expressed as follows for a single crop:

$$\frac{Y_a}{Y_p} = \prod_{i=1}^{m} \left[ 1 - k_{yi} \left( 1 - \frac{ET_{ai}}{ET_{pi}} \right) \right] \tag{1}$$

Where, $Y_a$ and $Y_p$, are actual crop yield and potential crop yield; $K_{yi}$ is crop response coefficient to deficit irrigation; and $ET_{ai}/ET_{pi}$ is the ratio of actual evapotranspiration at growth stage $i$ to potential evapotranspiration at growth stage $i$ . The above relation will be used in this study. Substitution of the ratio of water used to potential water demand ($W_a/W_p$) for $ET_a/ET_p$ in Eq. (1) will yield:

$$\frac{Y_a}{Y_p} = \prod_{i=1}^{m} \left[ 1 - k_{yi} \left( 1 - \frac{W_{ai}}{W_{pi}} \right) \right] \tag{2}$$

Here, Agro-Ecological Zone Method–AEZM (FAO, 1978-81) was used to compute potential crop yields, employing radiation data along with corrections for the climate and for the crop. Potential evapotranspiration for each growth stage was also determined using Penman-FAO method as explained in Doorenbos and Pruitt (1977) with relevant crop coefficients effected.

The distribution of applied water can be assumed as a uniform function. This typical distribution is shown in Fig. (1). In the practices, a gross irrigation depth ($H_g$) is applied to compensate for a soil water depletion or required depth ($H_n$). However, a deficit irrigation depth ($H_d$) is producted due to non-uniformity irrigation. A deficit coefficient ($C_d=H_d/H_n$) quantifies the magnitude of this factor. Mantovani et al. (1995) proposed a relation between the deficit coefficient and evapotranspiration deficit as follows:

$$1 - \frac{ET_{ai}}{ET_{pi}} = C_{di}(1 - p_i) \tag{3}$$

Where $p$ is the fraction of $ET_p$ supplied by other sources from irrigation (e.g., rainfall and capilary rise). Substituting Eq. (3) into Stewart and Hagan's simple empirial model yields,

$$\frac{Y_a}{Y_p} = \prod_{i=1}^{m} \left[ 1 - k_{yi} C_{di} (1 - p_i) \right] \tag{4}$$

The $C_d$ quality indice depends just on the uniformity of water distribution in the irrigation system, on the $H_g$, $H_n$ (Mantovani et al., 1995; and Li, 1998). The $C_d$ value may be determined by the following Equations.

If $H_n \langle H_{max}$,

$$C_d = \frac{H_d}{H_n} = \left[ \left( 1 - 2CU_{ch} + H_n / H_g \right) / \left( 8 - 8CU_{ch} \right) \right] \left[ 1 - \left( (H_g / H_n)(2CU_{ch} - 1) \right) \right] \tag{5}$$

If $H_n \rangle H_{max}$,

$$C_d = \frac{H_d}{H_n} = 1 - \frac{H_g}{H_n} \qquad (6)$$

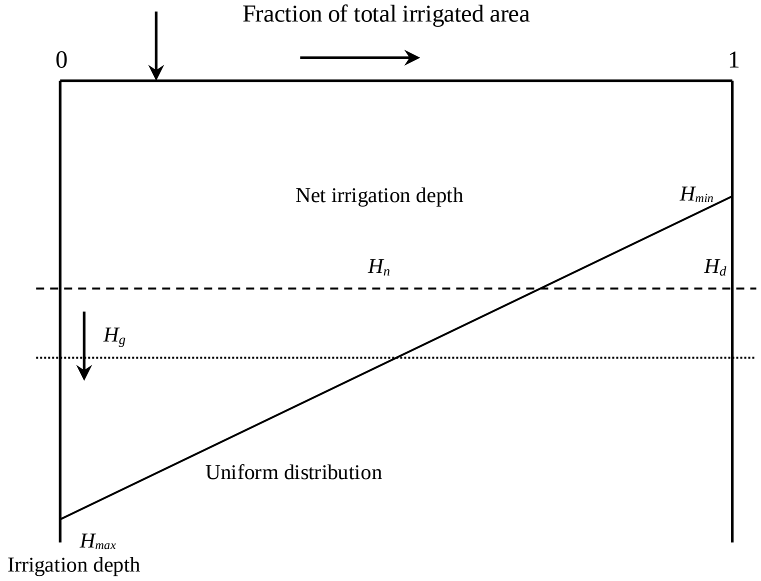


Figure 1. Uniform distribution of applied water

The objective function for a single crop of the cropping pattern can be expressed in terms of the difference between potential and actual performances of that crop (Eq. 7). In this equation, $Z$ is the objective function and $y_{pi}$ and $y_{ai}$ are the potential and actual yield values at the growth stage $i$, respectively.

$$Z = \sum_{i=1}^{m} \frac{1}{y_{pi}} (y_{pi} - y_{ai})^2 \qquad (7)$$

Eqs. (7) and (2) yields,

$$Z = \sum_{i=1}^{m} \frac{{k_i}^2}{{W_p}^2} (W_{pi} - W_{ai}) \qquad (8)$$

For $n$ crop, Eq. (8) may be showed as the following Equation:

$$Z = \sum_{j=1}^{n} \sum_{i=1}^{m} \frac{{k_i}^2}{{W_{pij}}^2} (W_{pij} - W_{aij})^2 \qquad (9)$$

Minimizing the value for this objective function (Eq. 9) will determine the optimal irrigation depth at every growth stage as well as the total irrigation depth of the crop under all water regimes. Optimization of the function was accomplished using Ms Excell Solver. Water constraint functions can be simply represented as below. $W_T$ designates total depth of water available from both surface and subsurface resources.

$$\sum_{j=1}^{n} \sum_{i=1}^{m} W_{(ai)j} \leq W_T \qquad (10)$$

$$\sum_{i=1}^{m} W_{ai} \leq \sum_{i=1}^{m} W_{pi} \qquad (11)$$

$$W_{ai} \rangle 0 \qquad (12)$$

We used the objective function of the productivity ratio of net profit to volume of water used in the irrigation network as expressed below in order to determine the optimal cropping pattern.

$$Max((B/Vol)_S) = Max\left( \frac{\sum_{j=1}^{n} B_j . A_j}{\sum_{j=1}^{n} A_j . D_{gj}} \right) \qquad (13)$$

Where, *(B/Vol)s* is the ratio of net profit to volume of water used in the system (*WP*); $B_j$ is the net profit resulting from growing crop *j*; $A_s$, the cultivated area for crop *j*; $D_{gj}$, gross optimal irrigation depth for crop *j*; and *k* is the crop number in the pattern. Net profit from each crop ($B_j$) is obtained from the following relation:

$$B_j = (B_m + B_l)_j - (C_l + C_w)_j \qquad (14)$$

Where, $B_m$ and $B_l$ are profits from the main crop and the secondary crop *j*, respectively; and $C_l$ is labor costs and all other associated costs including land, planting, growing, and harvesting costs, and $C_w$ is irrigation water cost of crop *j*. Irrigation water cost is a function of the total allocated water to the crop (Rls/$m^3$). All profit and cost values were considered from the presented reports by Office of Statistics and Information Technology, Ministry of Jihad–e–Agriculture of Iran (2005 and 2006).

In order to maximize the above objective function (Eq.13), the following constraints had to be taken into account:

$$A_j \geq 0 \tag{15}$$

$$A_{Min(j)} \leq A_j \leq A_{Max(j)} \tag{16}$$

$$\sum_{j=1}^{m} W_j . A_j \leq W_T . A_T \tag{17}$$

Where, $A_j$ is cultivated area for crop *j*; $A_T$ is total cultivated area irrigated by the network; *and* $A_{Min(j)}$ and $A_{Max(j)}$ are minimum and maximum possible cultivable area for crop *j*, respectively.

## 2.2. Study area

The proposed model was applied to Gazvine Irrigation Network (GIN) in the northwest of Iran. Fig. 2 shows location of irrigation network in province of Gazvin on map of Iran. Annual precipitation and evaporation in the region are 312 and 1345 mm, respectively, and the average annual temperature is 13.2º C. The network covers an area of 57,000 hectares and its water is supplied from Taleghan Dam and 102 integrated water wells scattered along the network area. In other words, the area is dominantly irrigated by surface water, but in the recent past, irrigation by groundwater has been increased. Irrigation by groundwater resources may extensively be increased during dry years. The GIN was approved in 1967 and its first phase composed of deviation checks, main and lateral canals constructed by 1976. The second phase also covered the remaining channels and structures in 1991 followed by the third phase which created the Taleghan Dam and its reservoir in 2001. GIN now consists of the dam, reservoir, and deviation dams (Sangban and Ziaran) conveying tunnel and the extensive irrigation system of Gazvin plain. The dam receives the Taleghan River to shift it to the northern margins of farmlands in the plain, as well as supplying partial drinking water for Tehran. The network comprises of 94 km main canal, 220 km canals II (12 branches), 33 km lateral channels III (158 branches), and 550 km subsidiary channels IV, with 30,000 branches and related outlets.

The overall 5-year plan adopted by Gazvin Irrigation Management Co. (GIM) could organize 30,000 local farmers' under 158 irrigation associations and 9 unions dominated by an apex Federation. Since 2002, organization and transferring network management to CBOs (Community-Based Organizations) deserved central priority and agenda by GIM, which fortunately, led to successful implementation. This initiative was basically accepted and supported by the Ministry of Jihad–e–Agriculture, and the National Water Resource Management followed by assignment of GIM as the national pilot for PIM commencement. Implementing Irrigation Management Transfer (IMT) initiative in Gazvin, has resulted in numerous cultural, social and economic impacts especially in the area of improvement of irrigation management and has created structural changes towards the great objective (i.e., Equitable distribution of water) in the network.


Figure 2. Location of irrigation network in province of Gazvin, Iran

Similar to other developing countries, food self-sufficiency is a major thrust in Iran. In the study area, cropping pattern and agricultural practices are prevailing as per their socio-economic requirements, which include self-sufficiency in food, employment, and availability of agricultural infrastructure. So, in the present study, the cropping pattern has been decided considering following factors:

1. Self-sufficiency of food: therefore wheat has been proposed as a major crop.
2. Employment: labour intensive crops to increase the employment opportunities.
3. Area availability: depending upon socio-economic needs, the crop area constraints are considered.

4. Availability of water for irrigation: to maximize the overall water productivity of irrigation network concerning of total water availability.

Considering to amount of water available and other socio-economic, around 70 % of the land along the network is annually allocated to crops while the remaining 30% is allocated to orchards or left on fallow. The crops of the cropping pattern in the region often include: wheat, barley, pear, corn, sugar beet, alfalfa, sun flower, cucumber, onion, potato, tomato, bean, and lentil. The irrigation systems commonly used across the network are furrow and border. Winter crops just include wheat and barley; and all others are summer crops. In this study, the values for the crop response coefficients to deficit irrigation were estimated from the values proposed in Doorenbos and Pruitt (1979) with regional corrections effected. The values for the period of each growth stage and maximum root depths were selected on the basis of field investigations. Also relative crop areas under cultivation were determined from the minimum and maximum percentages of observed cultivated areas in the region during 15 recent years.

# 3 Results and discussion

## 3.1 Total water availability

In order to investigate the conditions of the water resources in the study area, 30-year (1976-2005) statistics of the meteorological stations in the region were used. The SPI (Standardized Precipitataion Index) was used to analysis of water regimes during the studied period. However, the years of 1998, 1990, and 2001 were considered as wet, dry, and normal years in the study area, respectively. Based on the analysis, the volume of the water available from integrated water wells (groundwater resources) was estimated 21 million $m^3$ for the wet years over different months of the year. The volume of yearly water available from both surface and ground water resources for the different water regimes were presented in Table (2). The results show that in dry years, the water available across the irrigation network compare to wet and normal years will reduce by 47% and 37%, respectively; a finding that must be taken into account in selecting the cropping pattern.

Table 2. Volume of yearly water available from surface water and groundwater resources (million $m^3$)

| Water regime | Wet | Normal | dry |
|---|---|---|---|
| Water available from surface resources | 145 | 118 | 68 |
| Water available from groundwater resources | 21 | 30 | 43 |

## 3.2 Optimal demand water and cropping pattern

In order to maximize the overall water productivity, Eq. (13) was solved taking account of Eq. (14) and the constraints functions of (15) to (17) using Ms Excell Solver. The values of $CU_{ch}$ and $p$ parameters are assumed 0.3 and 0.2, respectively. The results of optimisation of the cropping pattern are presented in Table (3). This table shows the optimal cultivated area values for each of the crops in the cropping pattern under each water regimes. The results show that the greatest cultivated areas belonged to wheat which were 23599 and 19350 ha for wet and dry years, respectively. The lowest cultivated areas were obtained for sun flower which were 5.2 and 6.5 ha for dry and wet years, respectively. The optimal allocated water of crops was determined using Eq. (9). The objective function (Eq. 9) was solved taking the constraints functions of (10) to (12). Fig. (3) shows the optimal allocated water of each crop under different water regimes. The values for wheat were estimated 292, 367, and 377 mm for dry, normal, and wet years, respectively. The highest values were related to alfalfa which were 707, and 902 mm for dry and wet condition, respectively. The optimal allocated water values of irrigation network was considered 5500 mm (dry years), 6700 mm (normal years), and 6750 mm (wet years).

Table 3. Optimal cropping patterns under different water regimes

| **Crop** | **Cultivated area (ha)** | | |
|---|---|---|---|
| | **Dry** | **Normal** | **Wet** |
| Wheat | 19350 | 21153 | 23599 |
| Barley | 2800 | 2800 | 2800 |
| Corn | 1053 | 1053 | 1500 |
| Pear | 774 | 774 | 774 |
| Lentil | 77 | 77 | 77 |
| Sun flower | 5.2 | 6.5 | 6.5 |
| Sugar beet | 1204 | 1634 | 1634 |
| Cucumber | 645 | 860 | 860 |
| Potato | 107 | 193.5 | 193.5 |
| Onion | 43 | 43 | 43 |
| Tomato | 1300 | 1591 | 1591 |
| Alfalfa | 3010 | 3010 | 3010 |
| Bean | 602 | 860 | 860 |

The calculations indicate that decreasing the cultivated area for wheat under dry years will yield a water productivity value, $(B/Vol)_{wheat}$, of 11.074 Rls/ML (1 Rls = 0.0012 $US) which shows a reduction of 2.936 Rls/ML as compared to the same index for wet years, 8.139 Rls/ML, (Fig. 4). In Fig. (4), using the values of the cultivated areas and the values of allocated water for each crop in the cropping pattern, the water productivity was computed and compared for the crops under different water years. Investigation of the results shows that under dry years, onion with 75.069 Rls/ML has the highest value while alfalfa with 3.054 Rls/ML has the lowest value of water productivity. Under wet condition, these ranks also belong to onion (89.049 Rls/ML) and alfalfa (7.002 Rls/ML), respectively.

Fig. (5) presents the water productivity value of each crop as a function of irrigation uniformity and water regime. In this analysis, the *P* value was assumed 0.2. The results illustrate that in the different water years, water productivity values increase as the $CU_{ch}$ increases. For example, the water productivity of alfalfa in wet condition is 35.258 and 17.541 Rls/ML for $CU_{ch}$ of 70 and 30 %, respectively. The conclude is because of increasing of the required irrigation depth to achieve a given level of crop yield due to the $CU_{ch}$ decreases. The results are similar to that of Li (1998) and Mantovani et al. (1995) for a uniform model in sprinkler irrigation.

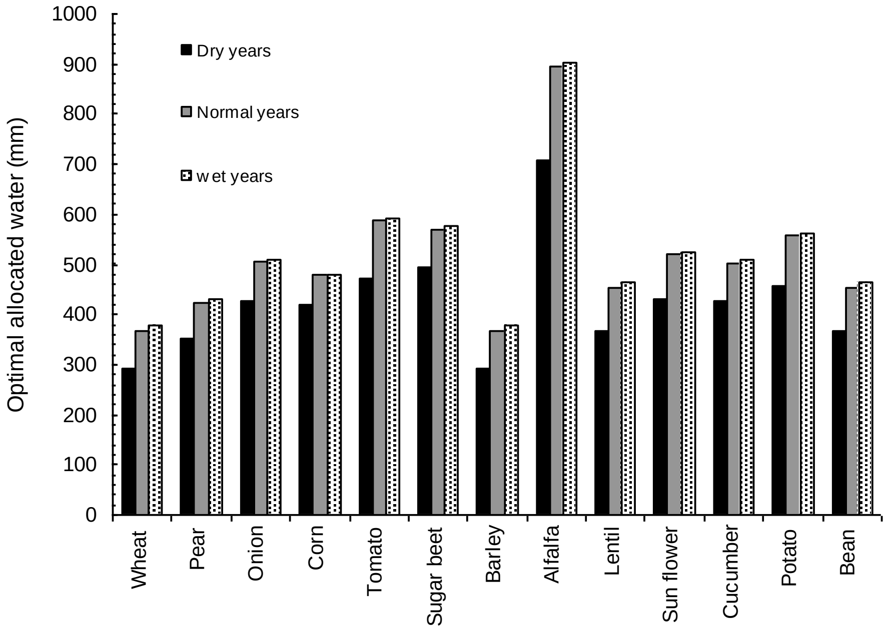


Figure 3. Optimal allocated water of each crop under different water regimes

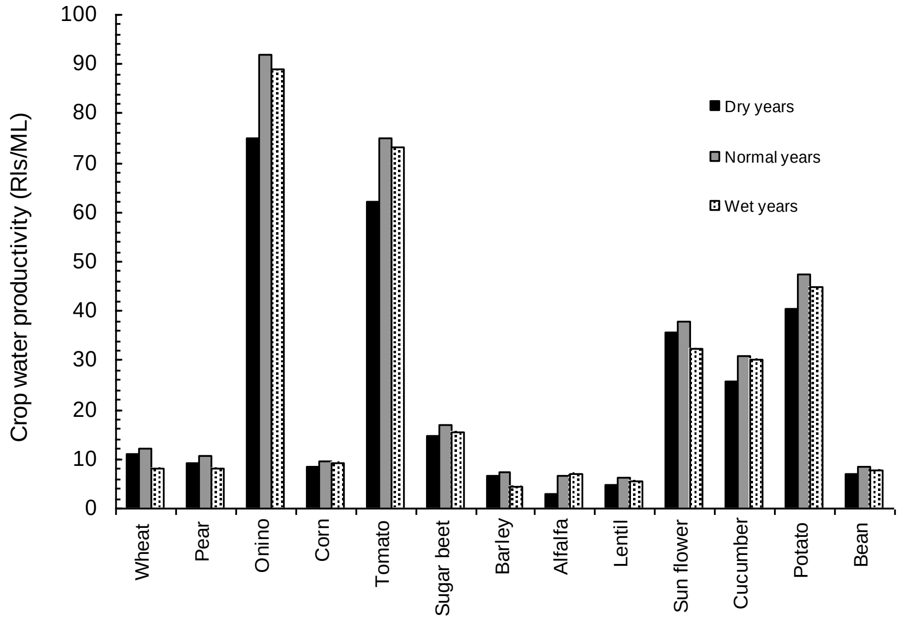


Figure 4. Crop water productivity of each crop under different water condition

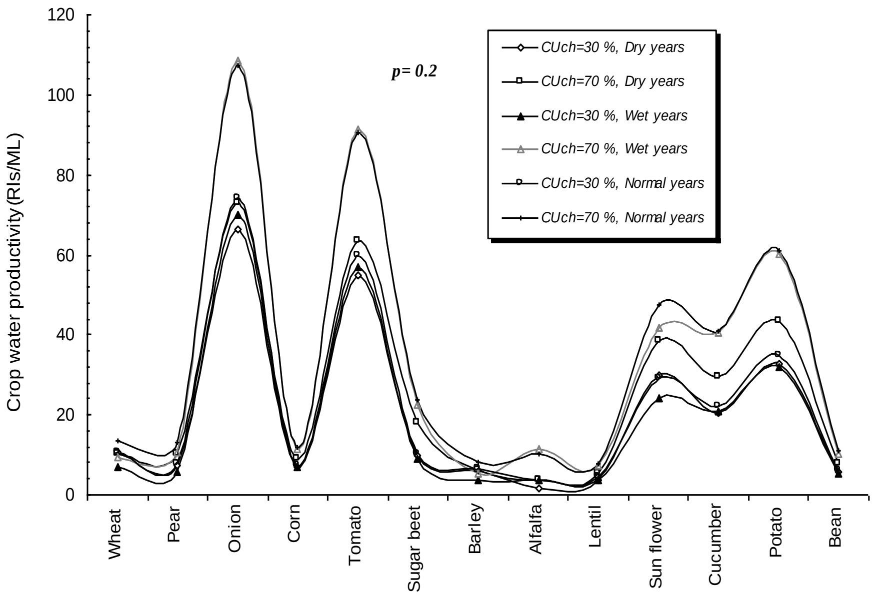


Figure 5. Water productivity of each crop as a function of $CU_{ch}$ and water regime

### 3.3 Evaluation of irrigation network productivity

The values for the overall water productivity of irrigation network (*(B/Vol)s*) for the optimal cropping pattern and under different water regimes are compared in Fig. (6). As seen in this figure, the value for the overall water productivity of irrigation network under cropping management can be increased to as high as 12.665 Rls/ML for dry water regime. For existing cropping pattern (2005), overall irrigation network productivity was estimated 10.553 Rls/ML. The values for this index are also estimated to be as high as 12.881 and 15.592 Rls/ML for wet and normal years, respectively. In other words, under dry years and with the optimal cropping pattern in practice and with appropriate deficit irrigation, the overall network water productivity can be improved. The maximum variations of this index may be fixed around 18% for different water regimes.

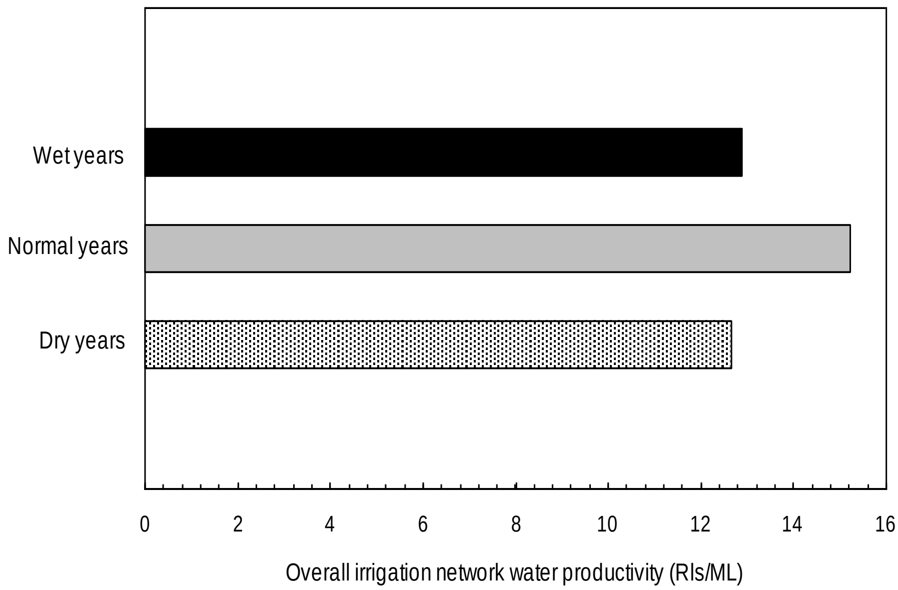


Figure 6. Overall water productivity of irrigation network based on optimal cropping pattern under different water regimes

## 4 Conclusions

Using a non-linear programming–based optimisation model, scope of maximizing water productivity defined as net benefit to the volume allocated water in an irrigation network in Iran has been investigated. Decision variables are the cultivated area and water allocated to each crop. The objective function of the model is based on crop-water production functions, production costs and crop prices. The model gives the optimal distribution of area and water to each irrigated crop and the water productivity. The model may be used to explore the possibilities of conjunctive use options of surface and groundwater in the study area, which would enhance the overall benefits from cropping activities. The results show that the highest cultivated areas belong to wheat crop with 23599 and 19350 ha for wet and dry years, respectively. The lowest values for the water productivity belonged to alfalfa, which were estimated at 3.054 and 7.002 for dry and wet years, respectively. The highest values of this index also belonged to onion, which were estimated at 75.069 and 89.049 Rls/ML for dry and wet water regimes, respectively. The analysis of the results indicates that under dry water regime, the overall network water productivity may be increased to as high as 12.665 Rls/ML. The findings lay emphasis greater than ever on the need for application of optimization models to determine optimal cropping pattern and water allocation in accordance with the potentials of existing water resources. The evaluations illustrate that the proposed model can be used as an effective tool to determine optimal irrigated cropping patterns under water scarcity constraints. The model determines the optimal distribution of areas and crops, the water allocation, and the profit. The model is relatively easy to apply, and has a great potential as a decision tool for cropping patterns in the command areas.

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